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Tandem Collaborative Control of Expressway Toll Station and Adjacent Intersection

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Abstract

To solve the problem of frequent vehicles interweaving and traffic queue overflow in the close range zone between expressway toll station and adjacent intersection, this study proposes an optimization method of tandem collaborative control for intersection connecting with toll station, analyzes the traffic characteristics when the on-ramps and out-ramps of toll station locate in the inner lanes of the intersection, and develops a mixed integer linear programming model for signal timing optimization with constraint variables of main-signal phase, pre-signal phase and flow partitioning considered. The results from extensive numerical analyses reveal that the optimized control can increase the capacity of toll stations and adjacent intersection by up to 32.74%, meanwhile, the increased proportion shows a trend of increasing first and then decreasing as the proportion of left-turn flow ratio on intersection increases.

Keywords

Traffic engineering, mixed integer linear programming, toll station, connected intersection, tandem intersection, expressway.

1. INTRODUCTION

Due to restrictions on urban land use, the distance between the suburban expressway toll station and adjacent intersection is usually short. In the area between the toll station and adjacent intersection, vehicles need to slow down and choose lanes in advance when entering the toll station or intersection, which leads to frequent vehicles interweaving in short distances and queue overflow from the intersection to the toll station exit or from the toll station entrance to the adjacent intersection, disrupting the stable operation of the toll station and adjacent intersection.

Previous research focused on improving the capacity of toll station and coordinating control with adjacent intersection to avoid vehicle queue overflow and improve the traffic efficiency. Ahmad et al. [1] searched for the optimal toll lane opening scheme through simulation evaluation. Yu and Mwaba [2] studied the configuration of toll lanes under different penetration rates of autonomous driving. Wang et al. [3] adjusted the lane allocation through measuring the congestion level of toll stations based on queue length. Kim [4] optimized lane allocation at toll stations by inducing vehicles to queue up on toll lanes with shorter queue length. Kumar et al. [5] and An et al. [6] studied the setting of tidal lanes at toll stations. Above researches aim to improve capacity and reduce traffic congestion of toll station and adjacent intersection, and the collaborative control for them have been expensively studied too. Kan et al. [7-8] developed a control model of expressway on-ramps to enhance the stability of on-ramp operation, in consider of the problem of vehicle queue overflow onto surface roads. Liu et al. [9] achieved collaborative control by dynamically adjusting the number of open lanes at toll station and the

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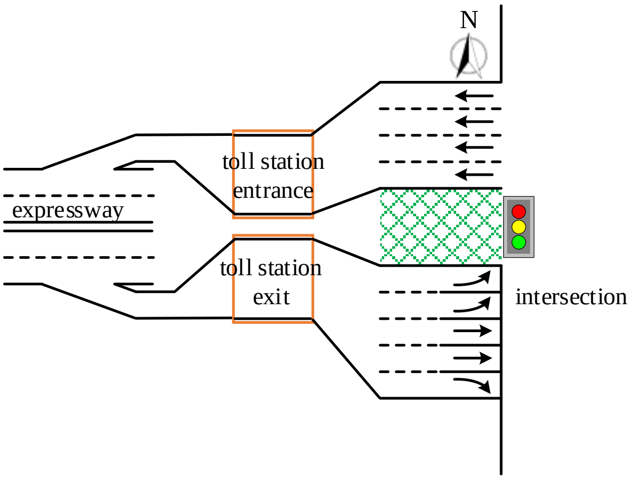
signal timing of adjacent intersection. Chen et al. [10] developed a macro control model to avoid vehicle queue overflow.

Some suburban expressways and urban roads are arranged in a three-dimensional and double-layer manner, resulting in that the inflow and outflow vehicles of the expressway interweave frequently with the vehicles on urban roads within a short distance between the expressway toll station and adjacent intersection, resulting in the reduce of the traffic capacity. Hitherto, no scholars have given a suitable solution to this issue. Chen et al. [11] applied the pre-signal control method of tandem intersection(TI) [12] to solve the problem of vehicle interweaving by traffic flow reorganization. The tandem intersection means that a pre-signal intersection(PI) set up on each approaching lanes, and the lanes between the pre-signal and main-signal intersection(MI) are divided into sorting areas(SA), then the movements on each leg of intersection are reorganized by pre-signal control. Compared with conventional intersections(CI), the weaving conflicts are avoid and traffic capacity is improved at TI [13]. At present, studies on TI have been widespread. Relevant scholars have carried out a series of studies from the aspects of delay calculation model [14], left-turning bicycles crossing [15], adaptive control [16-17], traffic safety [18], automatic driving [19-20], etc., but no scholars have applied it to the intersections which adjacent to toll stations.

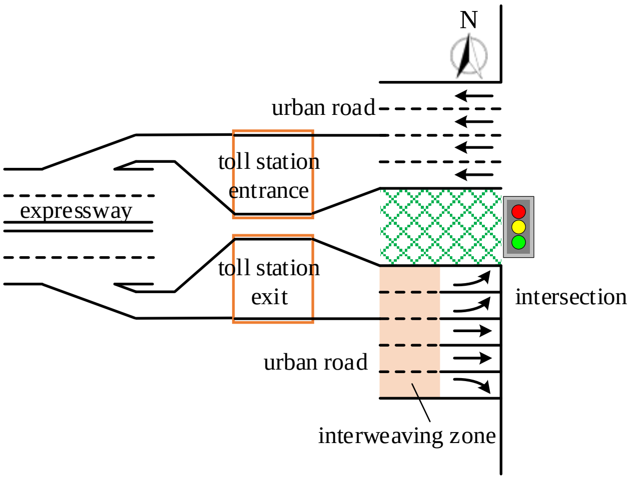
This article proposes a tandem collaborative control optimization method to avoid vehicle interweaving and vehicle queue overflow in the area between toll station and adjacent intersection, thereby improving the traffic efficiency and service level of the area.

2. TANDEM COLLABORATIVE CONTROL METHOD

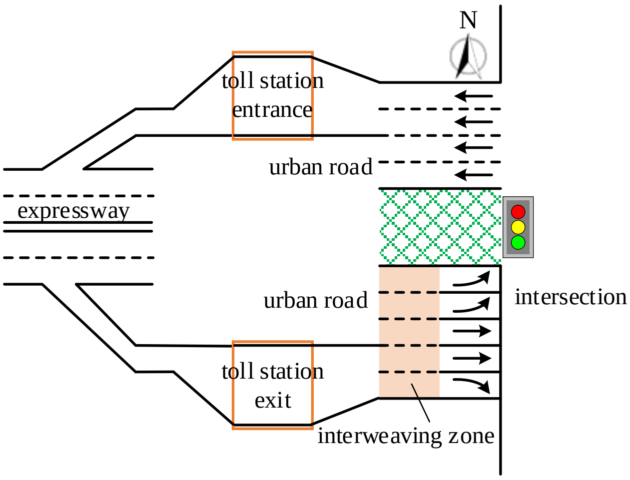
As shown in Figure 1, the composition types of suburban expressway toll stations and adjacent intersections include: the on-ramps and out-ramps of toll station including all approaching and receiving lanes of the intersection, the on-ramps/out-ramps of toll station locate in the inner lanes of the intersection exit/entrance, the on-ramps/out-ramps of toll station locate in the outer lanes of the intersection exit/entrance, the on-ramps/out-ramps of toll station locate in the middle lanes of the intersection exit/entrance, etc. Some types have been put into operation at the Jiahe Lianbian Toll Station and Jiahe Toll Station of Guangfojime Expressway, and Huangshi North Toll Station of Guangzhou Airport Expressway in China.



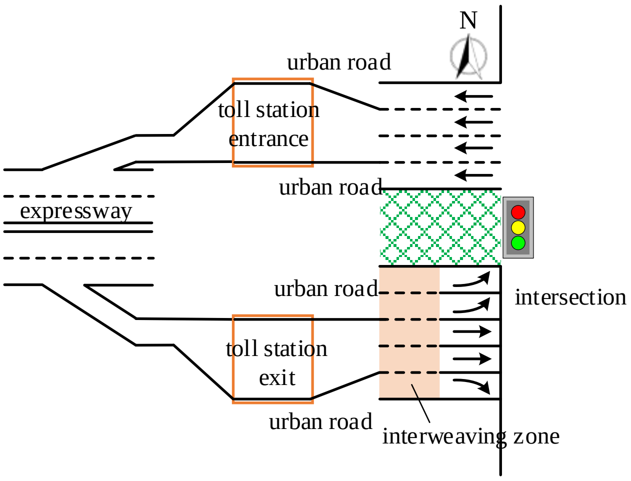
(a) The on-ramps and out-ramps of toll station including all approaching and receiving lanes of the intersection



(b) The on-ramps/out-ramps of toll station locate in the inner lanes of the intersection exit/entrance



(c) The on-ramps/out-ramps of toll station locate in the outer lanes of the intersection exit/entrance



(d) The on-ramps/out-ramps of toll station locate in the middle lanes of the intersection exit/entrance

Figure 1.Composition types of expressway toll stations and adjacent intersections

This study takes the type of toll station and adjacent intersection where the on- ramps/out-ramps of toll station located in the inner of receiving/approaching lanes of the intersection as the research object. As shown in Figure

1 (b), if the research object adopts conventional control, the outflow vehicles of the toll station and the vehicles on the urban road will interweave on the approaching lanes of the intersection, and only part of the approaching lanes of the intersection are allowed to turn left and go through, affecting the traffic efficiency of the intersection. As shown in Figure 2, if the research object adopts tandem collaborative control, the vehicle interweaving can be avoided by reorganizing the traffic flow at the pre-signal intersection, that is, the vehicles in lanes ① and ③ can be released in pre-signal phase 1, and the vehicles in lanes ② and ④ can be released in pre-signal phase 2. The signal controlled phase sequence scheme of the exclusive control presented in Figure 2 is shown in Figure 3. This study assumes that right-turn movements go through the right-turn exclusive lane and are not affected by traffic lights. Therefore, the impact of right-turn movements will not be considered in the following text.

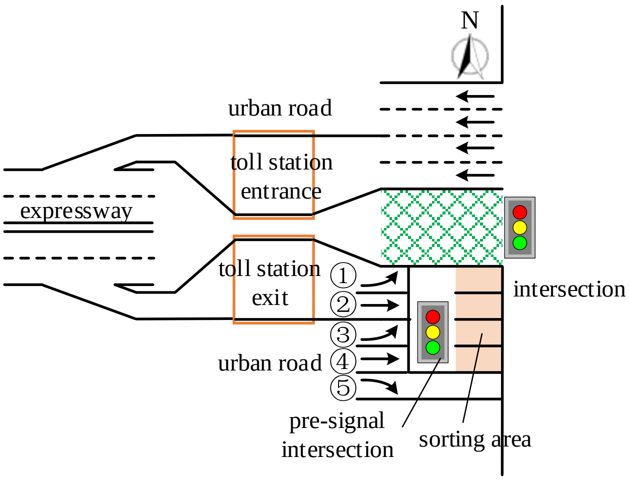


Figure 2.The research object

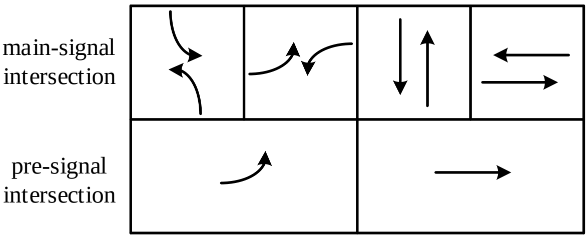


Figure 3.The signal controlled phase sequence scheme

3. MODEL FORMULATION

3.1 Constraints

3.1.1 Main-signal phase sequence constraints

As presented in Eq.(1), linear constraint with minimum and maximum constraint is constructed using the reciprocal of cycle length. The start and duration of green time within a main-signal cycle is between 0 and 1, and there is a minimum constraint on the green light duration, as shown in Eq.(2) and Eq.(3). In the main-signal phase sequence scheme, the start and duration of green time for the same phase is same, as presented in Eq.(4) and Eq.(5). Constraint (6) requires that the sum of green time and clearance time for two adjacent phases in all four phases is equal to a cycle. As shown in Figure 3, the relationship between the start and duration of green time at the front and rear phases of the main-signal and pre-signal is presented in Eq.(7)~(9).

$$\frac{1}{C_{\min}} \geq \delta \geq \frac{1}{C_{\max}} \tag{1}$$

$$0 \le t_i \le 1, \forall i \in I \tag{2}$$

$$g_{\min}\delta \le g_i \le 1, \forall i \in I \tag{3}$$

$$t_i = t_{i+4}, \forall i \in \{1,2,3,4\} \tag{4}$$

$$g_i = g_{i+4}, \forall i \in \{1,2,3,4\} \tag{5}$$

$$\sum_{i \in \{1,2,3,4\}} g_i + 4\alpha\delta = 1 \tag{6}$$

$$t_i = 0, \forall i \in \{3\} \tag{7}$$

$$t_{i'} = t_i + g_i + \alpha\delta, \forall (i,i') \in \{(3,1),(1,4),(4,2)\} \tag{8}$$

$$t_i + g_i + \alpha\delta = 1, \forall i \in \{2\} \tag{9}$$

where, δ is the reciprocal of cycle length /(s-1); $C_{\min}$ and $C_{\max}$ is the minimum and maximum cycle length /(s); t_i is the start of green time of movement i in a proportion of a cycle; g_i is the duration of green time of movement i in a proportion of a cycle; $g_{\min}$ is the minimum green time /s; α is the green light interval/s; i is the movement NO., $i \in I = \{1,2,3,4,5,6,7,8\}$ is the left-turn movement on west leg, through movement on west leg, left-turn movement on south leg, through movement on south leg, left-turn movement on east leg, through movement on east leg, left-turn movement on north leg, through movement on north leg, respectively.

3.1.2 Pre-signal phase sequence constraints

The PI is located on the west leg of the intersection that connects with toll station. The start and duration of green time within a pre-signal cycle is between 0 and 1, and there is a minimum constraint on the green time duration, as shown in Eq.(10) and Eq.(11). Constraints (12)~(15) ensure that the left-turn movement at the west leg of PI released after the through movement on the west leg of MI released completely and before the left-turn movement on the west leg of MI released completely, and the through movement at the west leg of PI released after the left-turn movement on the west leg of MI released completely and before the through movement on the west leg of MI released completely, meanwhile, the clearance time of lanes is considered.

$$0 \le t_{i,\mathrm{PI}} \le 1, \forall i \in \{1,2\} \tag{10}$$

$$g_{\min}\delta \le g_{i,\mathrm{PI}} \le 1, \forall i \in \{1,2\} \tag{11}$$

$$t_{i'} + g_{i'} + \alpha\delta - \frac{(L_{\mathrm{SA}} + L_{\mathrm{PI}})\delta}{\upsilon_i} + \beta\delta - 1 \le t_{i,\mathrm{PI}} + \mu_{i,\mathrm{PI}}, \forall (i,i') \in \{(1,2)\} \tag{12}$$

$$t_{i'} + g_{i'} + \alpha\delta - \frac{(L_{\mathrm{SA}} + L_{\mathrm{PI}})\delta}{\upsilon_i} + \beta\delta \le t_{i,\mathrm{PI}} + \mu_{i,\mathrm{PI}}, \forall (i,i') \in \{(2,1)\} \tag{13}$$

$$t_{i,\mathrm{PI}} + \mu_{i,\mathrm{PI}} \le t_i + g_i - \frac{\left(L_{\mathrm{SA}} + L_{\mathrm{PI}}\right)\delta}{\upsilon_i} - \beta\delta, \forall i \in \{1,2\} \tag{14}$$

$$t_{i,\mathrm{PI}} + g_{i,\mathrm{PI}} + \mu_{i,\mathrm{PI}} = t_i + g_i - \frac{\left(L_{\mathrm{SA}} + L_{\mathrm{PI}}\right)\delta}{\upsilon_i} - \beta\delta, \forall i \in \{1,2\} \tag{15}$$

where, $t_{i,\mathrm{PI}}$ is the relative start of green time for movement i on PI; $g_{i,\mathrm{PI}}$ is the relative duration of green time for movement i on PI; β is safe interval time for intersection /(s); υ_i is the speed of movement i /(m·s^{-1}); L_{SA} is the length of sorting area on west leg/m; L_{PI} is the length of PI on west leg/m; $\mu_{i,\mathrm{PI}}$ is a cyclic integer variable.

3.1.3 Traffic assignment constraints

Constraints (16) and (17) require that the release flow of movements at the main-signal/pre-signal shall not exceed the capacity of MI/PI. In constraint (18), the common flow multiplier of the entire intersection is required not to be greater than the flow multipliers of all movements at PI. The sum inflow of each ramp at the PI on the west leg is equal to the corresponding flow, as presented in Eq. (19). Constraint (20) requires that the capacity of PI is not greater than the capacity of MI.

$$\psi Q_i \le n_i s g_i, \forall i \in I \tag{16}$$

$$\psi_{\mathrm{PI}} Q_{i,j} \le n_{i,j} s g_{i,\mathrm{PI}}, \forall i \in \{1,2\}, j \in J \tag{17}$$

$$\psi \le \psi_{\mathrm{PI}} \tag{18}$$

$$\sum_{j \in J} Q_{i,j} = Q_i, \forall i \in \{1,2\} \tag{19}$$

$$\sum_{j \in J} n_{i,j} s g_{i,\mathrm{PI}} \le n_i s g_i, \forall i \in \{1,2\} \tag{20}$$

where, Q_i is the traffic demand of movement i /(pcu·h^{-1}); $Q_{i,j}$ is the traffic demand of movement i on ramp j /(pcu·h^{-1}); s is the saturation flow rate of a lane (pcu·s^{-1}); n_i is number of the approaching lanes for movement i; $n_{i,j}$ is number of the approaching lanes for movement i on ramp j; j is the on-ramp NO. of PI on west leg, $j \in J = \{1,2\}$ represents the urban road and out-ramps of toll station, respectively.

3.2 Objective function

In this paper, the objective function consists of two parts: maximizing the common flow multiplier of the toll station and adjacent intersection, and maximizing the common flow multiplier of the PI on west leg of the intersection. Maximizing the common flow multiplier of toll station and adjacent intersection is considered as the first level of the optimization objective, which is equivalent to maximizing the capacity of whole intersection. To maximize the capacity of PI, the common flow multiplier of the PI on west leg is considered as the second level of the optimization objective.

In sum, the objective function consists of two parts, as illustrated in Eq.(21).

$$\max \quad A_1\psi + A_2\psi_{\mathrm{PI}}, A_1 \ge A_2 \tag{21}$$

where, ψ is the common flow multiplier of the toll station and adjacent intersection; ψ_{PI} the common flow multiplier of the pre-signal intersection at west leg; A_1, A_2 is weight value, A_1 much greater than A_2.

The objective function shown in Eq.(21) and the constraints presented in Eq.(1)~(20) constitute the mixed integer linear programming model for signal timing optimization of intersection connecting with toll station, which can be solved using standard branch and bound algorithms.

4. NUMERICAL EXAMPLES

As presented in Table 1, this study takes the expressway toll station and adjacent intersection shown in Figure 2 as an example to set the parameter value, and three different traffic flow rates are set to compare the operational performance of conventional control and optimized control. The remaining parameter values are as follows: the weight value of objective function is 10^5 and 1, the minimum cycle length is 60 s and the maximum cycle length is 120 s, the minimum duration of green time is 10s, the green light interval time is 4 s, the safe interval time is 3 s, the length of sorting area is 60 m, the average speed is30 km·h^{-1}, the lane saturation flow rate is 1500 pcu·h^{-1}, the number of left-turn lanes is 2, the number of through lanes is 3, and the sum number of the approaching lanes is 5.

Table 1. The set of traffic flow

intersection type	traffic flow on west leg /(pcu·h^{-1})			traffic flow on south leg, east leg and north leg /(pcu·h^{-1})		
	turn left	through	sum	turn left	through	sum
conventional control	360	1440	1800	240	960	1200
optimized control	360	1440	1800	240	960	1200
conventional control	540	1260	1800	360	840	1200
optimized control	540	1260	1800	360	840	1200
conventional control	720	1080	1800	480	720	1200
optimized control	720	1080	1800	480	720	1200

4.1 Result analysis

The solution results of the signal timing optimization model for the example are shown in Table 2. It can be seen that there is no conflict between the release time for each movement of the optimized control signal timing, and the signal timing optimization model developed in this study is verified. Comparing the model solution results of optimized control and conventional control in Table 2, it reveals that under the three flow schemes, optimized control can improve the capacity of example intersection by 21.47%, 22.03%, and 22.55%, respectively. Hence, the optimized control method proposed in this study is a feasible approach to improve capacity and ease congestion for toll station and adjacent intersection.

Table 2. The solution results of the signal timing optimization model

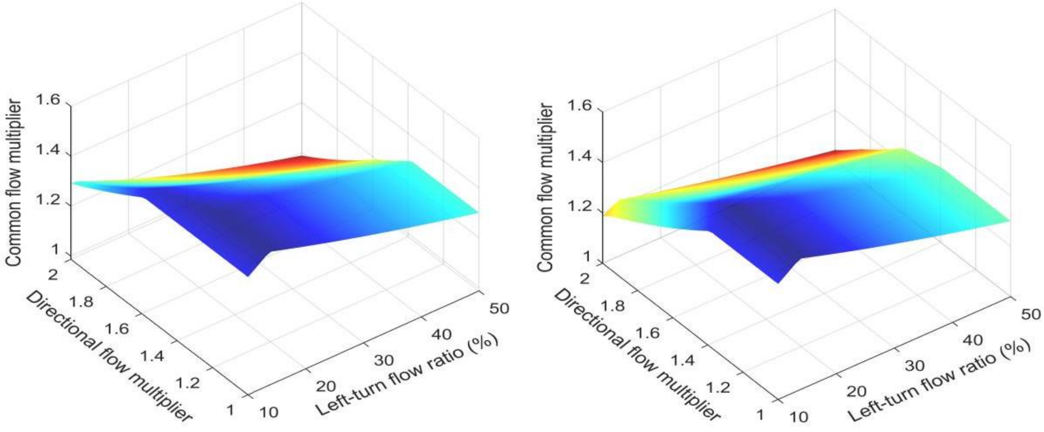
intersection type	the start and end of main-signal phase/s				the start and end of pre-signal phase/s		cycle length/s	common flow multiplier	relative proportion/%
	left-turn movements on west and east legs	through movements on west and east legs	left-turn movements on south and north legs	through movements on south and north legs	left-turn movements on west legs	through movements on west legs			
conventional control	[15,36)	[71,120)	[0,15)	[36,71)	—	—	120	1.18	—
optimized control	[18,36)	[76,120)	[0,18)	[36,76)	[113,22)	[37,107)	120	1.44	21.47
conventional control	[20,49)	[78,120)	[0,20)	[49,78)	—	—	120	1.13	—
optimized control	[24,48)	[83,120)	[0,24)	[48,83)	[113,33)	[48,107)	120	1.38	22.03

conventional control	[25,60)	[85,120)	[0,25)	[60,85)	—	—	120	1.08	—
optimized control	[29,59)	[88,120)	[0,29)	[59,88)	[113,43)	[58,107)	120	1.33	22.55

4.2 Sensitivity analysis

In order to analyse the changing trend of the capacity improving proportion under optimized control, this section performs the sensitivity analysis that the impacts of left-turn flow ratio and directional flow multiplier on legs of case intersection are investigated, and two situations which the proportion of urban road traffic is 30% and 40% are discussed respectively. The left-turn flow ratio refers to the proportion of the left-turn movements to the sum movements of left turn and through, with values ranging from 10% to 50%. The directional flow multiplier refers to the ratio of movements on west leg to the sum movements on south leg, east leg, and north leg, with values ranging from 1 to 2. The proportion of urban road flow refers to the proportion of urban road flow to the sum flow of urban road and toll station out-ramps. The values of other parameters are consistent with the case analysis.

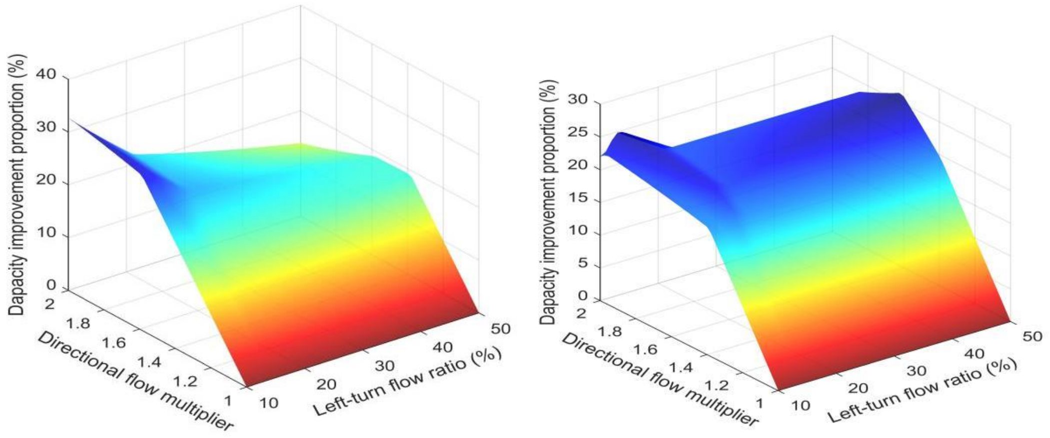
As illustrated in Figure4, the traffic capacity under optimized control shows a trend of first increasing and then decreasing with the increase of left-turn ratio. The reason is that when the left-turn ratio is low, the left-turn flow is a critical flow, and when the left-turn ratio is high, the through flow is a critical flow. However, as the directional flow multiplier increases, the traffic capacity under optimized control shows a trend of first remaining unchanged and then decreasing. The reason is that the west leg adopts a tandem intersection design, resulting in a significantly greater capacity than other legs. When the directional flow multiplier is small, the traffic demand on west leg does not reach its capacity, so the operation of the intersection is not affected. As the directional flow multiplier continues to increase, the traffic demand on west leg equals its capacity, causing a gradual decrease in the common flow multiplier.



(a) The proportion of urban road flow is 30% (b) The proportion of urban road flow is 40%

Figure 4.Trend of capacity changes under optimized control

As illustrated in Figure5, when the proportion of urban road flow is 30% and 40%, compared to conventional control, optimized control can achieve a maximum increase in traffic capacity of 32.74% and 26.32%, respectively. And as the directional flow multiplier increases, the proportion of capacity improvement under optimized control shows a trend of first increasing and then decreasing. In addition, the capacity is influenced by various factors such as the proportion of left-turn flow and the lane assignment of left turn and through, resulting in varying trends in the proportion of capacity improvement under optimized control as the proportion of left-turn flow increases in different situations.



(a) The proportion of urban road flow is 30% (b) The proportion of urban road flow is 40%

Figure 5.Trend of capacity changes

5. CONCLUSION

This study focuses on the expressway toll station and adjacent intersection, and proposes a tandem collaborative control optimization method with setting pre-signal intersection on the adjacent intersection, to reorganize traffic flow of the intersection and solve the problem of frequent vehicle interweaving in short distances between the toll station out-ramps and urban road.

The case analysis result demonstrates that optimized control under the three designed flow schemes can increase capacity of the intersection by 21.47%, 22.03%, and 22.55% compared to conventional control, effectively alleviating traffic congestion and improving traffic efficiency of the toll station and adjacent intersection.

The sensitivity analysis results show that optimized control can increase the capacity of the intersection by up to 32.74% compared to conventional control, and the proportion of capacity improvement under optimized control shows a trend of first increasing and then decreasing with the increase of left-turn flow ratio, and a trend of first remaining unchanged and then decreasing with the increase of directional flow multiplier.

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